Ground-Based Thermal-Infrared Investigations of Planetary Atmospheres

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Overview

• Science goals
• Observational results
• Influence on spacecraft results
  • Past example: context for the Galileo mission
  • Current example: input to Juno mission
• Future prospects
Goals

• Characterize atmospheric properties
  • Temperatures
  • Bulk atmospheric composition
  • Abundances of minor and trace gases
  • Cloud distribution

• Scientific motivation
  • Constrain global and local dynamical processes
  • Characterize energy transport
  • Constrain chemical processes
  • Constrain formation and evolution scenarios

• Programmatic motivation
  • Expand and enhance spacecraft results
    • Past & present: Galileo, Cassini, Juno
    • Future: JUICE, Europa Clipper, Dragonfly
Ground-Based Telescopes with Thermal-IR Instruments (Including 5-μm-only*)

- Subaru (COMICS until July 2020)
- Keck (NIRSPEC*, LWS)
- NASA Infrared Telescope Facility (NSFCam*, SpeX*, iSHELL*, MIRAC, MIRLIN, MIRSI, TEXES)
- VLT (UT3) (VISIR)
- Keck (NIRSPEC*, LWS)
- GTC (CanariCam)
Venus and Mars: oxidizing atmospheres

Temperature profiles determined by sensing well mixed CO\textsubscript{2} band brightness.

Venus: temperature variations are subtle except for polar regions.

Venus: trace species are highly variable, e.g. SO\textsubscript{2}/CO\textsubscript{2} ratios Encrenaz et al. (2003). TEXES @ IRTF.

- Mars: many trace species (some controversial)
  - CH\textsubscript{4}
  - HDO.
- Non-LTE emission from CO and CO\textsubscript{2} from ISO (Lellouch et al., 2000).
  - Probing upper atmospheric circulation, as on Venus.
- Carbonate signatures tentatively identified by Lellouch et al. (2000).
Atmospheric Structure of Jupiter and Saturn

**JUPITER**
- Stratosphere
- Haze layer
- Troposphere
- Ammonia ice
- Ammonium hydrosulfide ice
- Water ice
- Gaseous hydrogen, helium, methane, ammonia, water

**SATURN**
- Stratosphere
- Haze
- Ammonia ice
- Ammonium hydrosulfide ice
- Water ice
Use well-mixed CH$_4$ 7.8-μm emission to sense the stratospheric temperatures.

(C$_2$H$_6$ 12.2-μm and C$_2$H$_2$ 13.8-μm emission also sense the stratosphere but they are not well mixed.)

Use H$_2$ CIA 17.8- and 24.5-μm emission to sense the upper-tropospheric temperatures.

Use 8.8- to 11-μm emission to determine PH$_3$ and NH$_3$ abundances.
Radial thermal structure in ring particles

Longitudinal waves

→ Warm (summer) south polar region

↑ Hot south pole: region of forced downwelling air

Cool ring particles emerging from eclipse

IR mosaic of Saturn & rings at 18 µm from the Keck Telescope, February 2004
The pole itself is the warmest place on the planet. Southern latitudes are warmest, showing the influence of seasonal forcing.

Longitudinal waves.

12-element Keck/LWS mosaic of Saturn at 8.0 μm sensitive to stratospheric temperatures (4 Feb. 2004). (rings too faint to be visible)
We’ve been doing this for a while to distinguish between seasonal and non-seasonal effects.
Detection of thermal waves in Saturn: Cassini CIRS
Verified and expanded coverage with ground-based observations.

2003 Dec (IRTF: MIRSI) strong S. hemisphere waves

2004 Dec (IRTF: MIRSI) much weaker S. hemisphere waves

2005 Feb (IRTF: MIRSI) slightly stronger S. hemisphere waves

2008 May (VLT: VISIR) confirmation of the strong S. hemisphere waves seen by Cassini CIRS

...and confirmation of the fainter N. hemisphere waves
We discovered a variability of Saturn’s equatorial stratospheric temperatures over time.

We found that this was related to the variability in the vertical wave structure detected by high-resolution spectra of Saturn’s limb by the Cassini CIRS experiment.
The variations of the mean emission as a function of time are consistent with a period of 14.7 years, one half of Saturn’s orbital period.

This is a semi-annual oscillation, similar to the Earth’s semi-annual oscillation and related to the quasi-biennial oscillation (QBO).
Great springtime storm of 2010-2011 which produced an enormous upwelling at mid-latitudes in Saturn’s northern hemisphere.

The upwelling was consistent with cold temperatures in the upper troposphere.

Most spectacularly by the presence of two hot vortices in Saturn’s stratosphere, often called the ‘beacons’ because they dominated the 7.8-μm emission from the planet and looked like a slow version of a rotating lighthouse beacon.

After a few weeks, they merged to create a single “beacon”, defining a powerful stratospheric dynamical vortex.

This was found either to destroy or re-set the phase of the no-longer semi-annual oscillation.
Tracking of deep clouds

Detection of deep clouds from 5.1-μm imaging and scanned spectroscopy:

- Continue Cassini VIMS investigation of detailed cloud structure at depth
- Connection with 3- to 5-bar level atmospheric dynamics
- Connection with long-term behavior of cloud properties: detection of seasonal and non-seasonal effects.
Jupiter’s deep clouds detected in the thermal: $\sim 5 \ \mu \text{m}$
Sensitive to emission from clouds as deep as 5 bars.

Bright regions indicate deep clouds.

These are known as 5-\(\mu\)m “hot spots”.
Recent work with the VLT’s VISIR and Gemini North’s NIRI has made very high spatial resolution images from “lucky imaging”.
Due to limitations on the Galileo orbiter instruments, we had to characterize the region where the Galileo probe entered Jupiter’s atmosphere in 1995.

This had to be from the ground, despite Jupiter being 9° from the sun!

We used a 3-meter polypropylene “filter” to cover the entire primary mirror of the IRTF.

This admitted only light from $\lambda \geq 5 \, \mu m$. 
Case study: Galileo Probe Entry Location

- Galileo Probe results showed far less cloud / particulate opacity and water-vapor than expected
- “Anomally” low O/H ratio – surprising if the whole planet was this dry.
Classic Case study: Navigating the Galileo Probe Entry Location

• Solution: look closely at the entry site!

Ground-based observations clearly showed that the Galileo Probe had entered into an anomalously clear and dry region – a “5-μm hot spot” one of the clearest and driest areas in Jupiter
Classic Case study:  
Navigating the Galileo Probe Entry Location

• This was considered to be rather important
Classic Case study: Navigating the Galileo Probe Entry Location

• This was considered to be rather important

Knowledge of the anomalous sampling area turned out to be a major motivation for the Juno mission and its Microwave Radiometer experiment.
Jupiter’s temperatures

**Troposphere:**
Where convection is important

- **Great Red Spot**
  - $\leftarrow$ longitudinal waves

- $17 - 25 \mu m$ collision-induced $H_2$ absorption

**Stratosphere:**
Where heating by sunlight is important

- $7.7 - 8.0 \mu m$ CH$_4$ emission
Long-Term Observations of Jupiter’s Temperature Field:
Initial work done on behavior of temperatures using raster-scanned images: 1978-1994

Results found in:

← Jupiter’s stratosphere at ~20 mbar pressure
(Orton et al. 1991 Science 252, 537)

identification of the quasi-quadrennial (QQO) phenomenon
(Leovy et al. 1991 Nature 354, 380)

More recent high-resolution spectroscopy using the TEXES instrument has resolved vertical structure
(with Tommy Greathouse, IRTF observations)
**Long-Term Observations of Jupiter’s Temperature Field:**
Continues work done initially on behavior of temperatures using raster-scanned images: 1978-1994

Jupiter’s troposphere, at ~100 mbar pressure (Orton et al. 1994 Science 265, 625).

Those hints of non-seasonal variability are borne out by continued tracking.

Extensive evidence for periodicity that is non-seasonal and variable with latitude.
Juno-supporting observations: Subaru Telescope (2017 September 5)

2017 September 5 mid-infrared imaging of Jupiter, using the COMICS instrument on the Subaru Telescope (via Keck exchange time).
Juno-supporting observations: Subaru press release, 2019 August 23
composite map at 8.70 μm, sensitive to 0.6-1.0 bar cloud

Big storms in Jupiter, Great Red Spot (GRS), Oval BA (BA), SEB outbreak by arrow (1), vortices (3), super-clear regions (4), and large plumes by arrow (5). (Credit: Imke de Pater et al.)
Cold polar vortices: 360° longitude mapping: 2017 May 19-20 (PJ6)

Subaru COMICS 7.8 μm  Subaru COMICS 17.65 μm  JunoCam 890nm
Striking time variability discovered with COMICS

2017 Jan - Feb: Subsequent images show a similar morphology but (a) a short-term dependence on the amplitude of the local solar wind and (b) a longer-term disappearance over months.

2016 Jan 24
2017 Jan 13
2017 Feb 5
2017 May 18

North
South

7.9 μm: $T(\sim 5 \text{ mbar}), \text{CML}=186.2^\circ W$

2018 April 1, 10:19:00 UT
GRS Juno-Supporting Observations

Gemini N NIRI, 2017 May 18
near-infrared composite:
GRS has highest-altitude cloud/haze on the planet.

Subaru COMICS, 2017 May 18
8.7-\(\mu\)m image
GRS and environs have complicated cloud structure for particles \(\sim 600\) mbar.
Sorting out NH$_3$ vs temperature variations for Juno’s MicroWave Radiometer (MWR)

Optical Thickness (~700 mbar) from thermal emission in ~8-9 µm spectral window

500-mbar NH$_3$ VMR (ppm) from thermal emission in 9-11 µm NH$_3$ vib-rot band

T (300 mbar) from ~17-20µm thermal emission: sensitive to H$_2$ collision-induced absorption

Emission sensitive to NH$_3$ at 700 mbar

2017 Jul 13 VLT VISIR

2017 May 18 Subaru COMICS

2017 Jul 13 VLT VISIR

2017 Jul 11 MWR 1.38 cm
Retrieval of disk-averaged $T(p)$ for the troposphere from spectral regions controlled by well-mixed $\text{H}_2$ collision-induced absorption (CIA)

URANUS: Spitzer IRS Spectrum, 2007 Dec., near equinox

Global-mean temperature profile, composition
Fletcher et al. (2014) determined a fit to Akari IRC and ground-based (Gemini S) observations (I am behind schedule for Spitzer IRS analysis.)

- assumed a meridionally uniform abundance of $\text{CH}_4$ above the tropopause, using a value determined by Lellouch et al. (2010) from Herschel PACS CH$_4$ rotation-line spectral measurements.
- constraints also provided by center-to-limb structure in thermal imaging and spatially resolved spectroscopy.
Seasonal Contrasts: Uranus and Neptune

- Ice Giants Seasons:
  - Uranus 98° tilt at 20AU
  - Neptune 28° tilt at 30AU.
  - Different driving forces for meteorological activity.
Mid-IR Observations of Uranus: Troposphere

The Voyager IRIS experiment mapped tropospheric temperatures. Ground-based observations at giant telescopes, including Subaru, showed that these results were still consistent with Voyager one Uranian season later (Orton et al. 2015 Icarus 260, 94)

The hemispherical asymmetry observed in the tropospheric temperatures of Uranus is unlikely to be the results of seasonal changes in solar radiation.
Thermal IR Observations of Uranus: Stratosphere - $C_2H_2 \nu_2$ Band Emission

- Model for seasonal photochemical variability developed by Moses et al. (2018 Icarus 307, 124)
- $C_2H_2$ distributed assuming seasonal changes of insolation, with no changes of temperature

- Sluggish mixing in Uranus results in distribution of acetylene toward higher pressures where chemistry and diffusion time scales are large, so seasonal variations are small
Observations with VISIR, Very Large Telescope: 2006 September 1-2

Discovery images: hot spot at south in upper troposphere (17.6 μm and 18.7 μm) warm southern region in stratosphere with hot spot in methane (8.6 μm) and ethane (12.3 μm) that is “offset” from the pole (S at bottom in these images)
Future Observing Opportunities
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• COMICS at Subaru
  • 2020 A
  • 2020 B
  • 2021 A
  • 2021 B...
Future Observing Opportunities

- COMICS at Subaru
  - 2020 A
  - 2020 B
  - 2021 A
  - 2021 B...

- And, according to Subaru HQ apparently no past achievements, either!
Other Future Observing Opportunities

• MIRSI at the IRTF, currently with instrument problems
• TEXES at the IRTF (mostly) possibly at Gemini North
• VISIR at the VLT, due to return in 2020
• CanariCam at the GTC: October 20-μm test imaging was surprisingly successful on Uranus. We are waiting for service observing results.
• Mimizuku at TAU (2021?)
• MIRI observations with the JWST
  • Some guaranteed planetary time (Heidi Hammel) to be released publicly
  • Early Release Science (de Pater et al.) on Jupiter
• METIS at the ELT and MICHI at the TMT
Future (TMT) - Giant Planet I: Climate & Circulation

- What is the 3d circulation of giant planet atmospheres and the factors shaping variability?
- Aim to connect visible changes (clouds, colors, winds) to environmental changes (temperatures, composition, wind shear).
- 3D Reconstruction of atmospheric temperatures, composition, winds, clouds, etc.
- Suited to imaging and moderate-resolution spectroscopy, in the L- through Q-bands.

How does atmospheric circulation vary between planets?

Variation of climates

3.5 µm Reflectivity and aurora

5.0 µm Deep Clouds

Q-band 100-400 mbar T

13.0 µm Deep T and C₄H₂

8.6 µm Ammonia & Clouds

7.9 µm Stratospheric T

7.9 µm Stratospheric T
Giant Planet II: Temporal Changes

- Giant planet atmospheres evolve on timescales from:
  - Minutes (impacts)
  - Days (Plumes, storms)
  - Weeks (Belt/zone life cycles)
  - Years (seasonal evolution)

- The TMT would provide the same understanding of ice giants as we have for Jupiter/Saturn.

- Environmental changes underlying this variability:
  - Would benefit from simultaneous measurement of reflected sunlight and thermal imaging

- TMT diffraction-limited resolution provides good altitude coverage for temperatures, gaseous abundances and clouds:
  - Temperatures from N- and Q-band H₂ absorption and CH₄ emission imaging and spectroscopy
  - Gaseous abundances from N-band thermal emission, primarily from hydrocarbons
  - Cloud properties from <5 μm reflection spectroscopy, K-, M-, N- and Q-band center-to-limb behavior

Variation of climates

What drives atmospheric variability?

Saturn’s thermal emission
Orton & Yanamandra-Fisher 2005

Neptune’s thermal emission, Orton et al., 2007
Giant Planets III: Deep into the Clouds

- M-band provides a unique window – minimal reflected sunlight, minimum H$_2$ and CH$_4$ opacities allow deep sounding.
- Giant-planet cloud condensation region.
- M-band spectroscopy allows separation of gaseous species.
  - NH$_3$ for cloud-condensation
  - PH$_3$, AsH$_3$, GeH$_4$ for deep atmospheric circulation
  - CO for external influx of O-species.
  - CH$_3$D for cloud sounding, D/H ratio for origins.
  - High-temperature H$_3^+$ emission
- Never exploited for the ice giants before!

Jupiter’s 5-µm Window

Courtesy R.S. Giles, SwRI

Vortices at 5 µm from Keck. Credit: Imke de Pater, Michael Wong (UC Berkeley); Al Conrad (Keck), and Chris Go (Cebu, Philippines)
Giant Planet IV: Middle Atmosphere

• Wave activity may dominate energy transport and material distribution in planetary stratospheres.

• Investigate via:
  • (i) High-resolution sounding of Doppler broadened CH$_4$, C$_2$H$_6$ lines (3, 7, 12 µm)
  • (ii) Stellar occultations to probe atmospheric T/density structure (e.g., using Io hotspots as point source)
Terrestrial I: Trace Species (Venus)

- What causes the dramatic variability of gaseous species on Venus? We want to work towards a comprehensive climatology:
  - N-band shows CO$_2$, SO$_2$, H$_2$SO$_4$ features.
  - SO$_2$ shows dramatic variations.
- M-band non-LTE emission from CO (4.7 µm), CO$_2$ (4.3 µm) can be used to measure spatial variability in the mesosphere.
  - Sensitivity to gravity wave propagation/breaking
- But is Venus too bright for eELT/TMT?

Variation of climates

Nightside thermal emission 3-5 µm from Venus Express

Zasova et al., 2004

VIRTIS observations, Arnold et al., 2012

Variability of SO$_2$ mapped using ratios of SO$_2$/CO$_2$ lines at 7 µm, Encrenaz et al., 2013
Terrestrial II: Trace Species (Mars)

What are the sources and sinks of trace species in the Martian atmosphere?

- Sensitive search for trace species on Mars (e.g., controversial Martian methane).
  - CH$_4$ at 3.3, 7.8 µm
  - HDO at 3.7 µm, unsuccessful searches by ISO.
- Non-LTE emission from CO and CO$_2$ first detected by ISO (Lellouch et al., 2000).
  - Probing upper atmospheric circulation, as on Venus.
- Carbonate signatures in the M and N bands tentatively identified by Lellouch et al. (2000).
“Terrestrial III”: Titan Beyond Cassini

• Titan’s rich atmospheric composition considered as an example of a prebiotic atmosphere.

• Extensive studies by Cassini/VIMS and Cassini/CIRS came to an end in 2017.
  • TMT could continue these over a full Saturnian year.

• High-resolution imaging (reflectivity and thermal) and N-band spectra to understand:
  • Methane cycle and variable cloud activity (K- and L-band)
  • Seasonal evolution of circulation through temperatures, trace gases and cloud activity (N-band)

Titan’s atmospheric circulation during northern winter, Teanby et al., 2008

Variable cloud activity monitored by Keck in reflected sunlight, Roe et al., 2008.
‘Terrestrial’ IV: Titan Surface to Upper Atmosphere

- Surface variability from M-band: Using high-resolution infrared windows (e.g., M-band where CH$_4$ opacity at a minimum).
- Upper atmospheric studies from:
  - CO fluorescence near 4.7 µm allow measurement of external oxygen influx.
  - HCN fluorescence near 3 µm to understand upper atmospheric circulation.
Some hiccups on the way to the TMT
IF EVERYTHING SEEMS UNDER CONTROL - YOU AREN’T GOING FAST ENOUGH.

-Mario Andretti
... a lesson I try to carry into my personal life.
Questions ?
**Giant Planet IV: Planetary Aurora**

**How does solar wind control planetary aurorae and heating?**

- $\text{H}_3^+$ auroral emission allows mapping of giant planet ionospheres (temperature/density) by tracing heat flow within upper atmospheres.
  - Ionospheric flows coupled to magnetic field, connects planet to external environment.
  - Focus on auroral variability; but....
  - Non-auroral regions are driven by complex dynamics that comes from multiple sources, including low-latitude precipitation, upper atmosphere dynamics and upwelling heat
- How does upper atmospheric temperature change with altitude/latitude – a key question for planetary aeronomy!

- Cassini can image Saturn’s aurorae, but low spectral resolution prevents measurements of ionospheric properties
- Uranus $\text{H}_3^+$ hard to detect (first seen in 1992), but long-term upper atmospheric temperatures have decreased over time.
- Neptune $\text{H}_3^+$ still undetected, models predict it should be there!
- L-band measurements are required.
Thermal infrared observations from spacecraft:

Pioneers 10 and 11 at Jupiter and Saturn (1973, 1974)
InfraRed Radiometer (IRR)

Photopolarimeter-Radiometer (PPR)

Cassini at Saturn (2005-2017)
Composite InfraRed Spectrometer (CIRS)
(Heritage from Voyager IRIS)
Cassini CIRS survey observations of the northern hemisphere:

Show that the combined beacon is visible in stratosphere and upper troposphere.

Some wave structure might be present at low latitudes, but Lomb-Scargle periodogram analysis does not consider it to be above the 1% false-alarm level of credibility.
Jupiter also has thermal waves:  
See 100-mbar retrieved temperatures from:  
Broad distribution of the frequency spectrum of a thermal-wave spectrum in Jupiter’s upper troposphere